TARDEC

---TECHNICAL REPORT---

THE NATION'S LABORATORY FOR ADVANCED AUTOMOTIVE TECHNOLOGY

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TARDEC

Efficiency and Performance Test
of the
ZF LSG 2000 Transmission

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Development, and Engineering Center
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A ZF Friedrichshafen AG transmission, the LSG 2000, underwent performance and efficiency testing at the U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC). Results obtained indicated that the LSG 2000 performed better than the transmissions it was compared with while under low speed, high torque conditions, but performed worse than the comparison transmissions while under high speed, low torque conditions.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION:

The LSG 2000 transmission is one of several transmission produced by ZF Friedrichshafen AG of Germany. The purpose of a transmission is to transfer the power from the engine, along with the input from the driver, to the wheels in such a form so that it accomplishes what the driver desires. The transmission allows more torque or speed in the proportion that is necessary to accomplish the given task at hand.

A transmission contains many gears that are used to change the input power, made up of torque and speed, into output power, also made up of torque and speed, but in different proportions. It is desirable to have large amounts of torque and relatively low speeds available when a vehicle is moving very slowly. In this way the wheels (or tracks) will not spin very fast (which could cause slipping) but will generate a large amount of force to propel the vehicle forward. This is especially useful if the terrain is very muddy or while moving up an incline.

For a vehicle which is traveling fast, it is desirable to have low torque and high speeds at the wheels. The vehicle, under this condition, requires little force to move it, the inertia does most of this work. A vehicular transmission must be able to accommodate fast and slow movement in both forward and reverse motion.

The LSG 2000 transmission was purchased and testing was requested and funded by the Foreign Material Exploitation office located at the U.S. Army Tank-automotive and Armaments Command (TACOM) in Warren, Michigan, USA. This transmission is designed to operate in a tracked vehicle weighing a maximum of slightly over 88,000 pounds (40,000 kg) and has a maximum input power of nearly 805 HP (600 kW). It has four forward gears and two reverse gears. In addition, it contains a torque convertor with a maximum torque multiplication of 2.8.

OBJECTIVE:

The objective of this test was to determine the efficiency and performance of the LSG 2000 transmission. Data obtained in the testing process can be evaluated allowing a comparison between the LSG 2000 and other existing transmission's in the Army's fleet. In addition, it allows for comparison with other foreign and domestically produced transmissions not currently in use by the Army, and to help evaluate prototype transmissions as well as conceptual designs.

RESULTS AND CONCLUSIONS:

Some of the most useful information generated in a technical report comes from comparing the tested component to other similar components. In light of this, figure 1 is presented which shows a comparison of efficiencies for different transmissions previously looked at by the Army. The transmissions vary from newer to older to experimental to theoretical. The LSG 2000 has been inserted into this figure and is shown as the thin dashed line. Though thorough testing of the LSG 2000 was unable to be completed, a complete set of data for the first three lock-up gears is presented. Due to failure, a complete set of fourth gear data was unobtainable, but the small amount of data recorded in fourth gear is presented.

The transmission that indicates the highest efficiency, the ATT 1064, is strictly a theoretical transmission, never making it past the paper stage. The CVX 650 and the HMPT-1000 are experimental transmissions that have yet to be integrated into a military vehicle. The remaining three have been incorporated into Army ground vehicles. The HMPT-500 is in the Bradely Fighting Vehicle

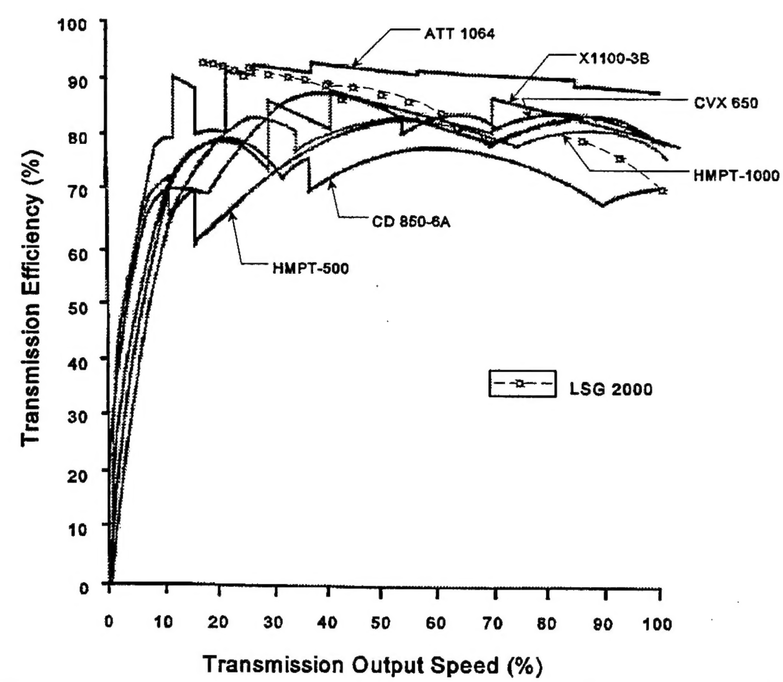

Figure 1 : LSG 2000 Efficiency Comparison

(M2/M3), the CD 850-6A is in a tank (M60) and the X1100-3B is used in the Abrams Main Battle Tank (M1).

The LSG fairs pretty well with respect to the other transmissions presented in the illustration. Favoring the low speed, high torque side of the spectrum the LSG 2000 had better efficiency than the competition while at the high speed, low torque condition, the LSG 2000 was just shy of the pack.

The performance of the LSG 2000 by itself is illustrated in figure 2. This dual purpose chart shows how the output horsepower attainable by the LSG 2000 varies with the output speed. The transmission output is directly related to the speed a vehicle would be going utilizing this transmission. Though this chart does not show torque, since horsepower, speed and torque are all interrelated (Horsepower =Torque x speed/5252.11), the torque can be calculated. This would then show that the torque at the low speeds is much greater than that generated at the high speeds - exactly what should be expected from a transmission. Relation to the top chart is used to show the speed point that the engine is operating at in order to attain the results illustrated in the lower portion.

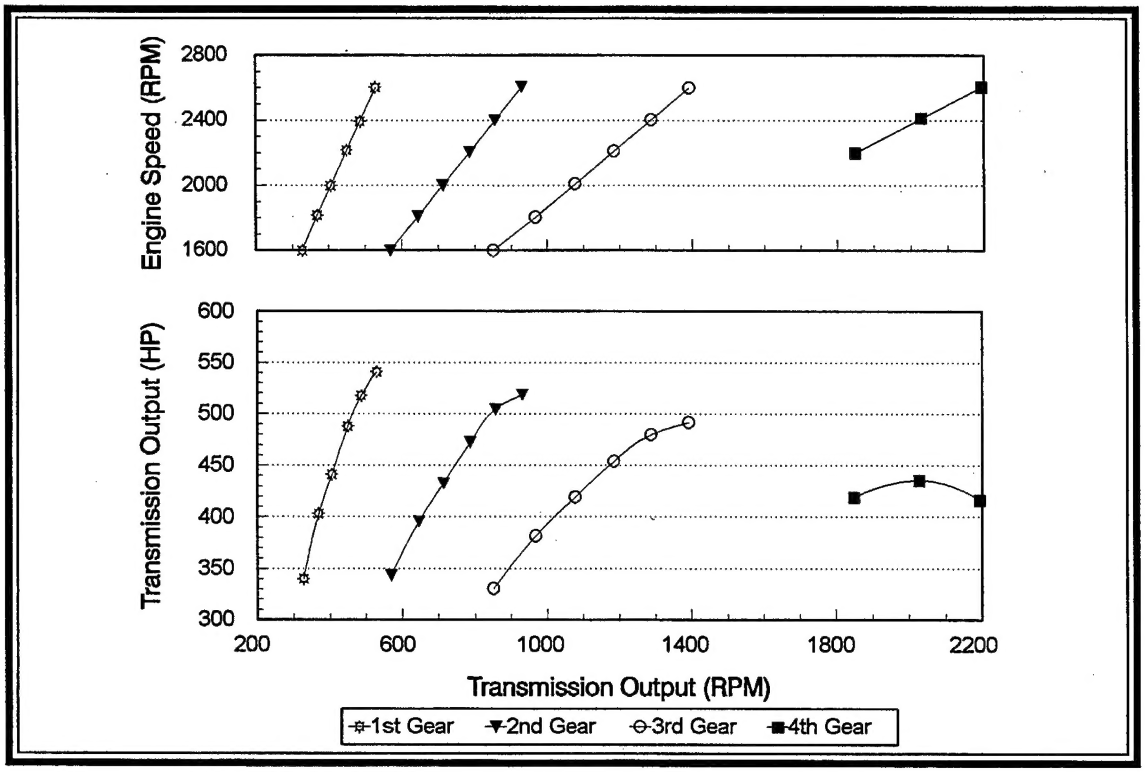

Figure 2 : LSG 2000 Full Throttle Performance Curves

DESCRIPTION:

The LSG 2000 transmission is one of a family of transmissions produced by ZF Friedrichshafen AG of Germany. It is a fully automatic transmission with powershift steering. The transmission is based on a modular design principle containing a total of nine separate modules each located in the transmission housing. It has four forward gear ratios and two in reverse. The gear ratio's are as follows:

Forward:	Gear 1:	4.15	Reverse:	Gear 1:	4.52
	Gear 2:	2.36		Gear 2:	1.38
	Gear 3:	1.57			
	Gear 4:	1.00			

The LSG 2000 offers a choice of input and summarizing gears in addition. For the testing conducted at the Tank Automotive Research, Development and Engineering Center (TARDEC), the input gear ratio was 0.917 and the summarizing gear ratio was 1.296.

The torque converter in the LSG 2000 allows for torque multiplication of up to 2.8:1. This, along with the mechanical gears, allows for a maximum torque multiplication of roughly 15:1. There is a lock-up clutch allowing the torque convertor to achieve a mechanical ratio of 1:1 when speed instead of torque becomes more important.

A torque convertor is a device used to help the transmission multiply torque beyond what the mechanical linkages would normally allow. The basic functioning of the convertor is similar to a fluid coupling. A torque converter can be simplified to three basic components, oil, an impeller and a turbine. The impeller is attached mechanically to the engine side. Attached to the transmission side is the turbine. In between would be the fluid layer of oil. As the impeller spins, it forces the oil in the convertor to also spin in a circular pattern. When this oil hits the turbine, the turbine starts to spin due to the reactive forces placed upon it. The force of this oil on the turbine causes an increase in torque as compared to the input torque on the impeller side. A lower speed will also be noted on the output side as compared to the input. This higher torque created by the rotating oil yields the so-called "torque multiplication" of the converter. The greater the difference in speeds between the input impeller (spinning faster) and the output turbine(spinning slower), the higher the torque multiplication ratio will be. The output speed of the turbine adjusts such that the necessary torque output at the wheels can be achieved. As a torque convertor lacks a mechanical connection between components it is inherently more inefficient. Therefore, as the speed of the turbine approaches the speed of the impeller, a lock-up clutch is engaged to mechanically connect the system

together. This eliminates the inefficiency that would be occurring it the fluid coupling was still intact.

A transmission input of just over 800 HP (600 kW) can be accepted by the LSG 2000, while maximum engine output speed is variable to a degree due to the ability of changing the input drive gear.

The physical characteristics of a component are very important due to the limited amount of under armor volume in a combat vehicle. For the LSG then the height is 31.61 inches (803 mm), the length is 40.94 inches (1040 mm), and the width is 38.78 inches (985 mm).

The engine mated to the LSG 2000 for this test was a Cummins VTA-903. This diesel engine is capable of producing 600 GHP (447 kW) at 2600 rpm and 1241 ft-lbs (1683 Nm) of torque at 2300 rpm.

DISCUSSION:

The LSG 2000 was installed and instrumented in building 212, test cell 5 at TARDEC, a sub-group of TACOM, also located in Warren, Michigan, USA. Figures 3 thru 5 show the installed and instrumented transmission prior to the start of testing. The Cummins VTA-903 engine is shown in figure 6. The engine and transmission were separated from one another. Torque shafts and propeller shafts were used to connect the two together as shown in figure 7. The control room layout and instrumentation is shown in figure 8. The transmission was controlled by using a "selector switch" provided by ZF Friedrichshafen. The selector switch, as shown in Figure 9, has the purpose of, among other things, changing transmission gears, indicating certain steering conditions and enabling the retarder. Power output from the LSG 2000 transmission was absorbed by using two absorption dynamometers. Each dynamometer has the ability to handle speeds up to 3000 RPM and torques of up to 50,000 ft-lbs (67,791 Nm).

Efficiency testing was to be performed twice for this transmission. Each time it would be tested in the four forward gears and both reverse gears. In addition the torque converter efficiency was also to be determined by testing. The difference was that for the initial testing, the transmission would be using SAE 10W oil (the oil specified by the manufacturer), whereas for the second set of efficiency tests, the transmission would be using SAE 15W-40 oil. The Army today strives to bring logistical support costs down. By way of doing this, a unified oil is sought, this oil being SAE 15W-40. Upon consultation with ZF Friedrichshafen AG of Germany, they concurred to test with this alternate oil.

Though efficiency testing was the primary goal of this project, other tests were also to be performed. These tests included a pivot steer test and a no load spin loss test. The complete test plan for the LSG 2000 is found in appendix A.

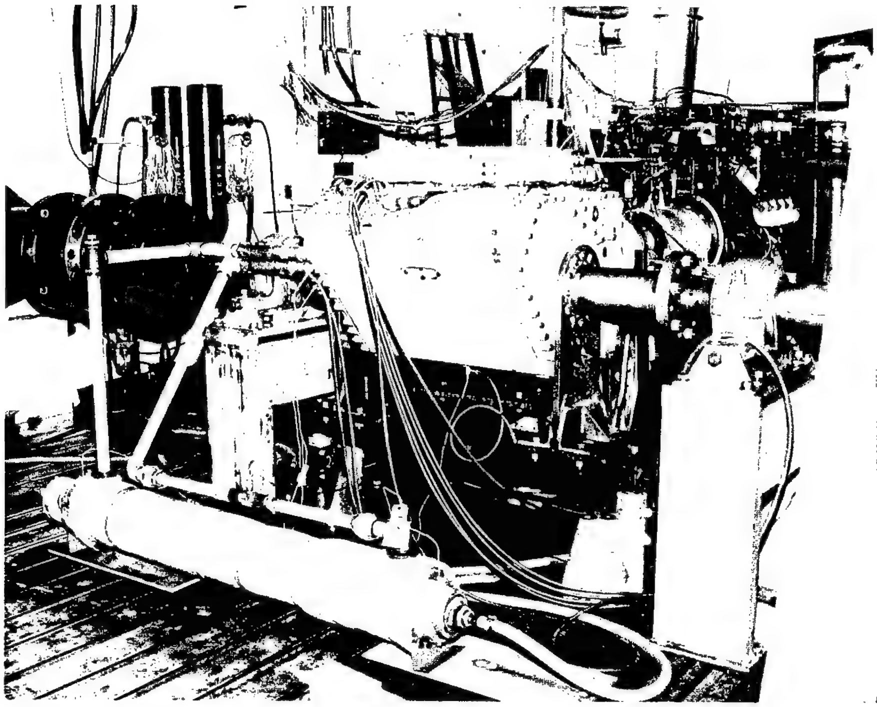

Figure 3 : Front 3/4 View of LSG 2000 as Installed in Cell 5

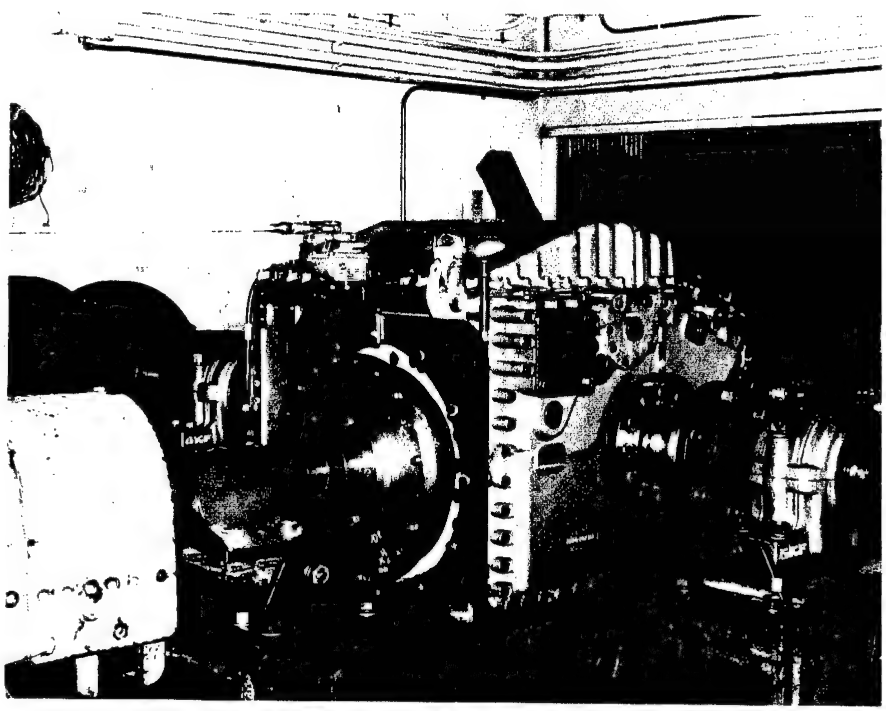

Figure 4 : Back 3/4 View of LSG 2000 as Installed in Cell 5

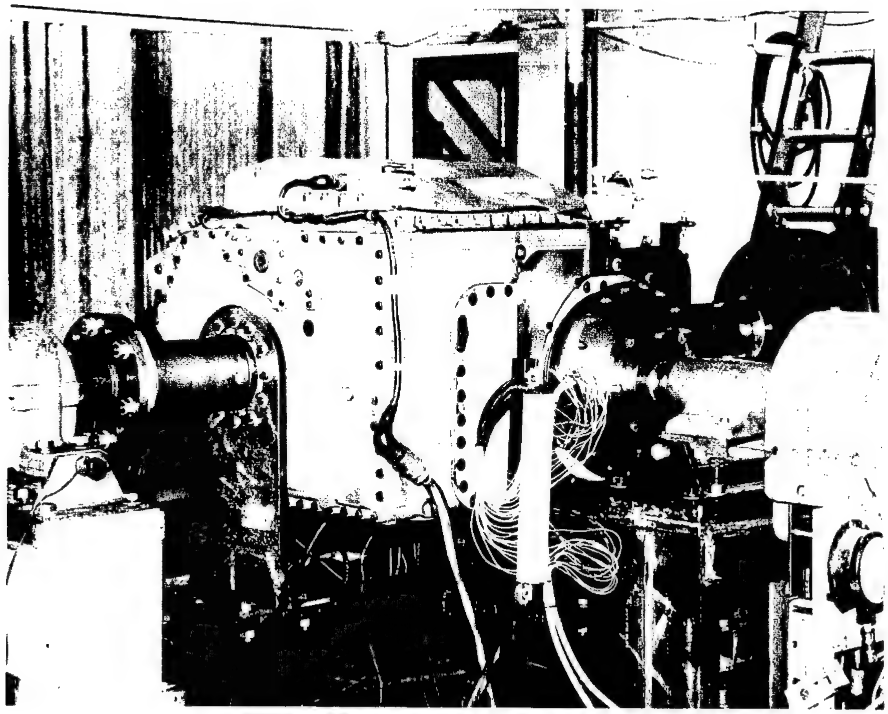

Figure 5 : Back 3/4 View of LSG 2000 as Installed in Cell 5

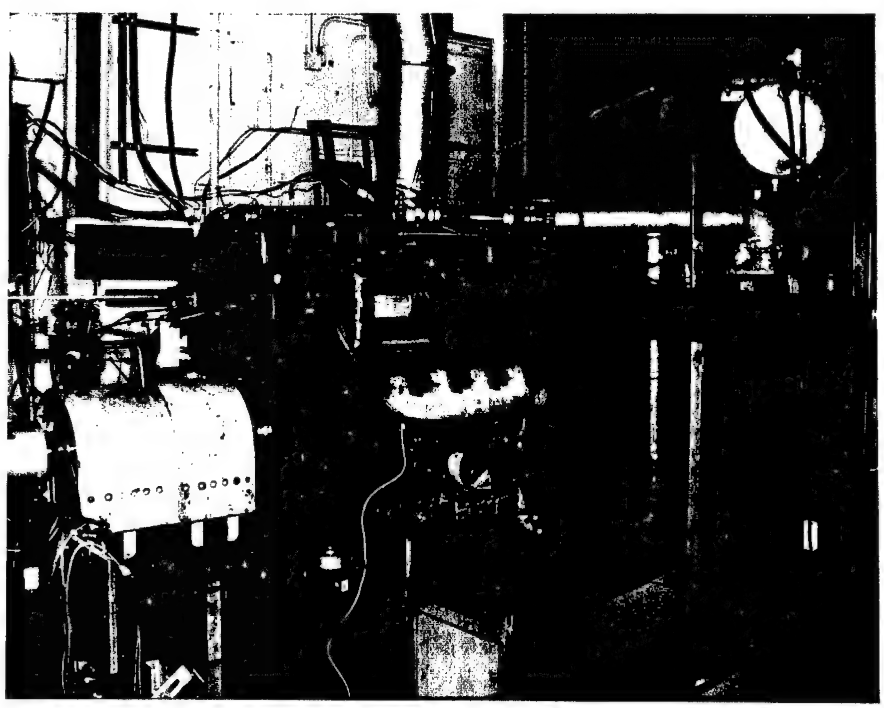

Figure 6 : Cummins VTA-903 Diesel Engine

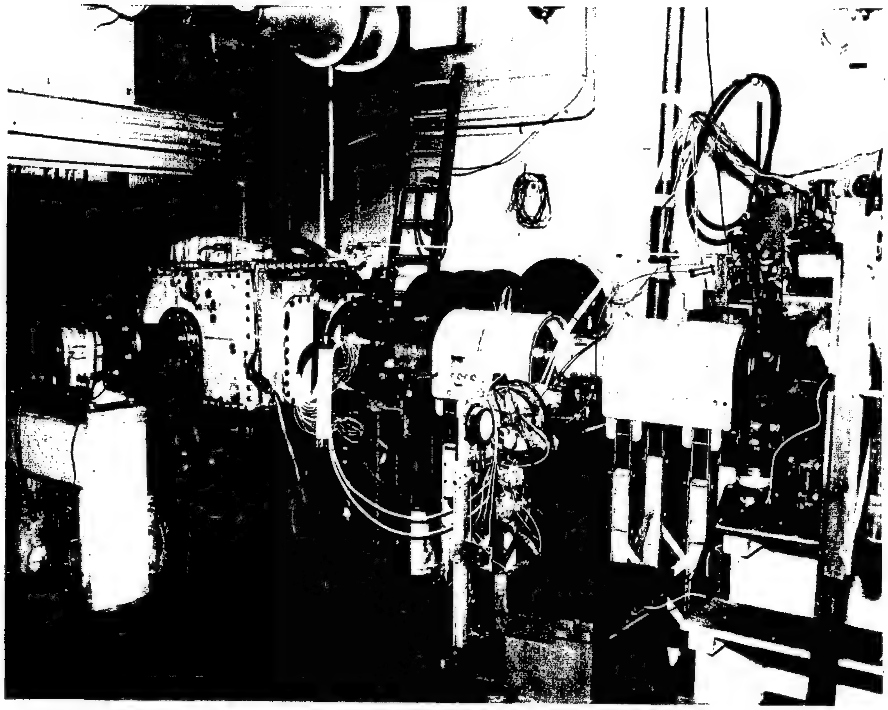

Figure 7 : Test Layout Showing Connection Between Engine and Transmission

Figure 8 : Test Cell 5 Control Room and Instrumentation

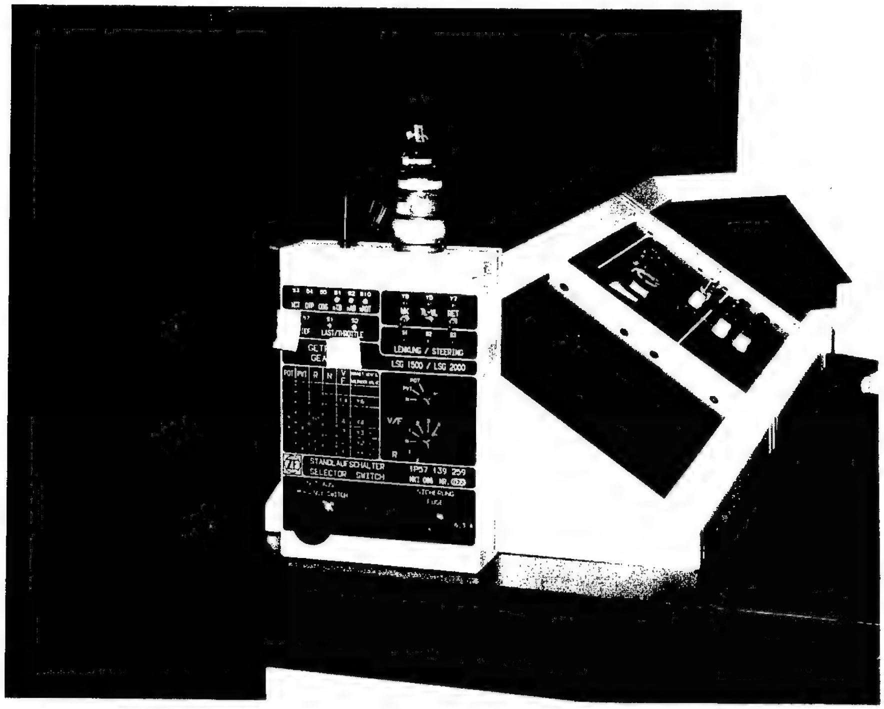

Figure 9 : Selector Switch

Testing with SAE 10W oil was performed in forward gears one thru three. A set of sample data, for second gear, can be found in appendix B.

While running in fourth gear at approximately 2200 rpm the north dynamometer cooling oil reached a critical temperature that initiated automatic test shutdown. The dynamometer oil temperature exceeded 140°F (60°C) which was specified as the test termination limit. A second heat exchanger was added to the system to lower the dynamometer oil temperature to acceptable limits.

Testing resumed in the fourth gear condition. While proceeding down from a transmission output speed of 2400 to 2200 a fire was observed in the north output shaft between the pillow block and the transmission. The test was immediately terminated and the fire suppressed. The fire was caused by the ignition of grease in the shaft connection between the pillow block and transmission connecting shaft. Figure 10 shows a pillow block, while figure 11 shows how a pillow block is orientated in relation to the rest of a test setup.

Investigation of this failure revealed the extent of the damage to the entire test layout. Several components on the TARDEC output shaft were severely scored and would require replacement. But, more importantly, the dust deflector on the transmission's output shaft had been pressed into the bolt pattern behind it. Figure 12 shows a properly oriented transmission output shaft.

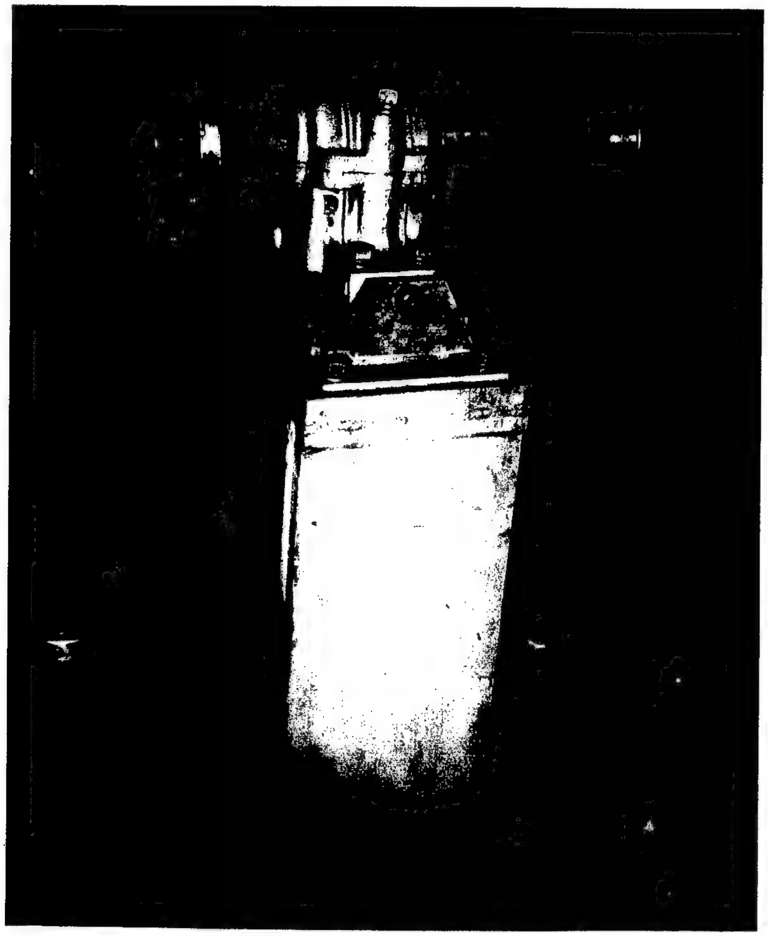

Figure 10 : Pillow Block

Disassembling this output shaft from the transmission housing revealed that the failure had caused a heat build-up in the transmission's output shaft causing oil seal failure, bearing failure and some mechanical failure do to shearing effects. For a more complete explanation of the failure, refer to appendix D. The main gearbox could still be rotated and appeared to be functional. Do to the extent of the damage in this portion of the transmission, as a minimum, a new output shaft would need to be obtained. Consultation with ZF Friedrichshafen AG of Germany indicated the potential that did exist for the main gear box also to have been damaged. ZF Friedrichshafen recommended that we contact one of their representatives from ZF Industries in the U.S. to evaluate the extent of the damage and specify all the parts that were needed for repair.

There was no service contract in place with ZF Germany to allow for engineering support in case of a failure during testing. Accordingly, we would be required to pay for a service visit in order to have the damaged transmission inspected by a ZF Industries representative. Lack of funding for this project (for both the consultation and repair parts) in addition to requiring the issuing of a

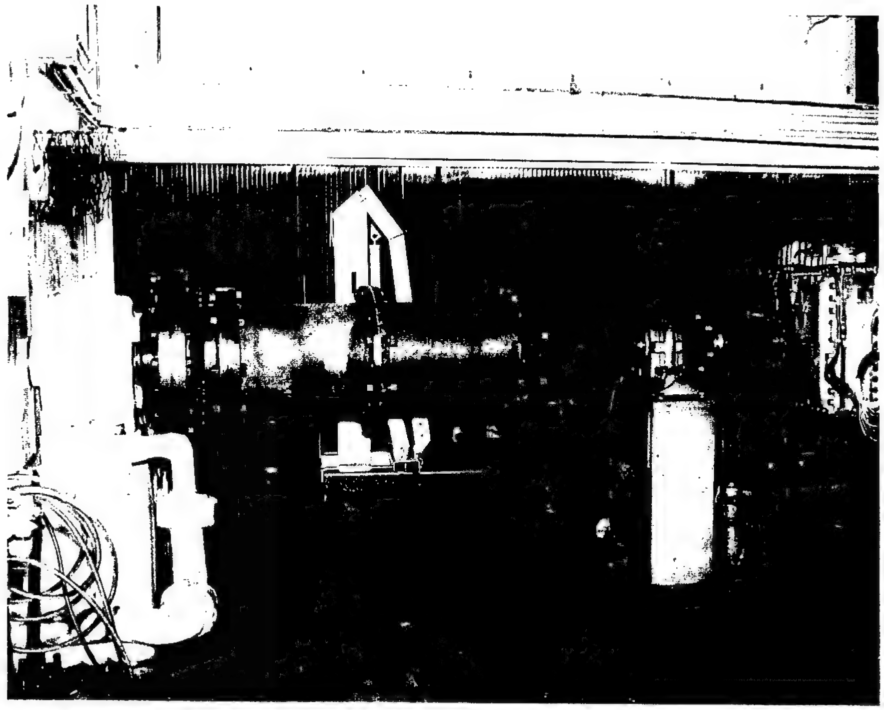

Figure 11 : Dynamometer Connection to LSG 2000 Using Pillow Block

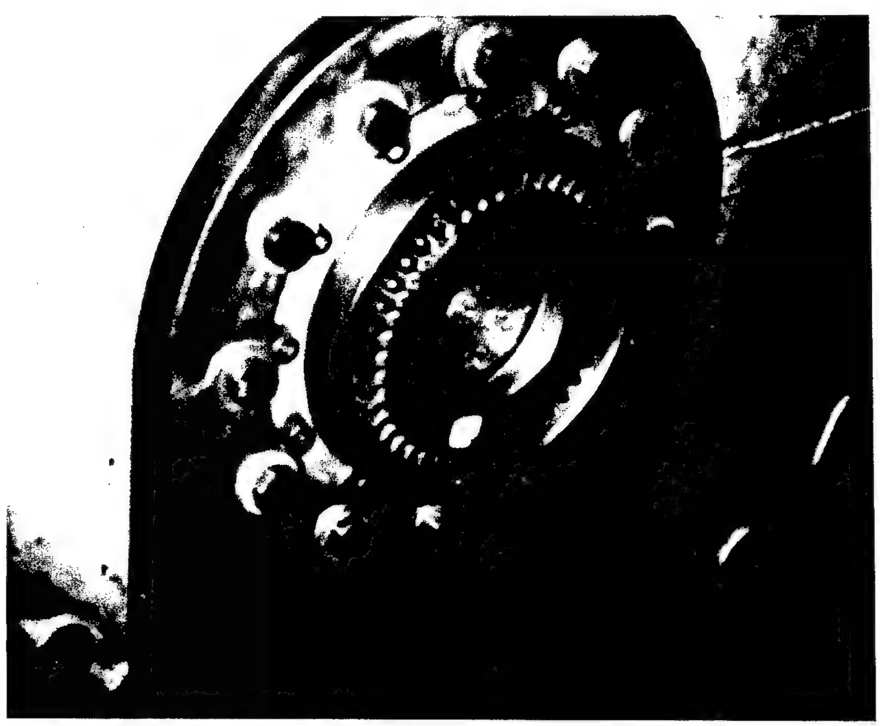

Figure 12 : Dust Deflector Position on a Good Transmission Output Shaft

contract to receive ZF Industries's consulting services forced us to terminate the test at this point.

Although the test was terminated after completing only three gears with SAE 10W oil, the data for these three gears is available. An illustration of the full load efficiency of the four gears tested is shown in figure 13. As is typical in a transmission, a steady decrease of overall efficiency can be seen as the higher gears and speeds are achieved.

The highest efficiency points found in the three gears completing testing occurred under the full load condition. In lock-up, they were found to be 92.2%, 91.5% and 88.0% in first, second and third gears respectively. The optimum efficiency in fourth gear was unable to be determined.

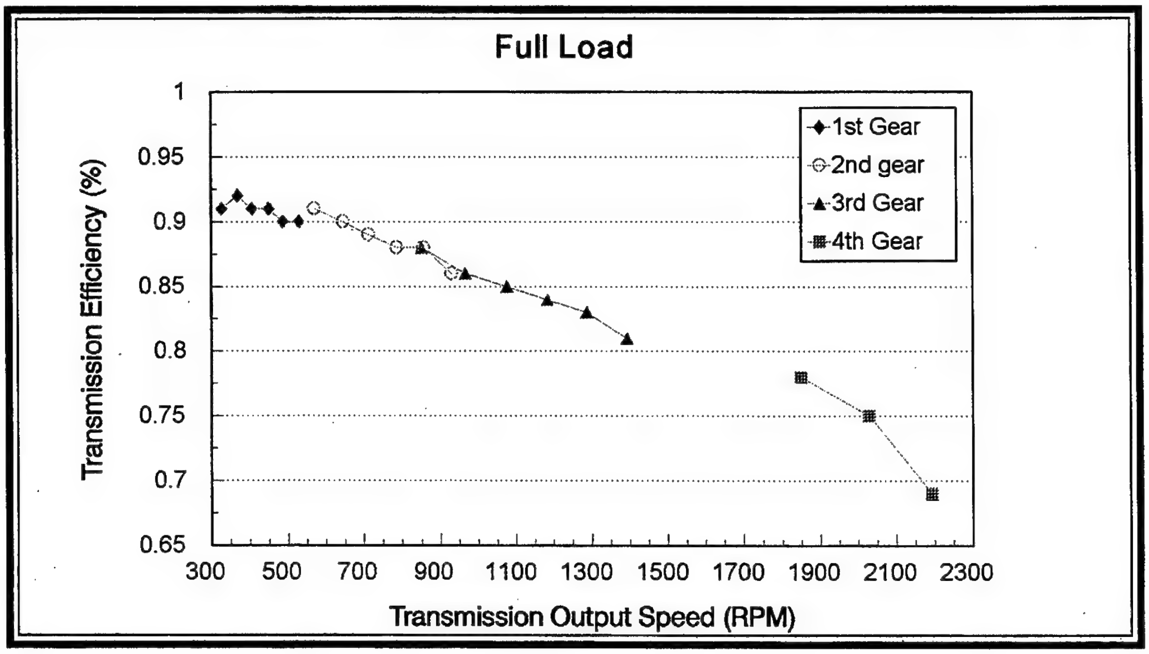

Figure 13 : LSG 2000 Full Load Transmission Efficiencies

The testing separated each of the transmission gears into four different loads, full load and three partial loads, 75%, 50% and 25%. When partial load is referred to, it simply means that the engine power output is at the stated percentage of its maximum possible output, or, how far down the gas pedal is pushed. This allows a more realistic portrait of efficiencies that will most commonly be observed in an actual military vehicle. Typically, the less load that is exerted the less efficient the system will be. The partial load test results for the LSG 2000 in gears one through three are illustrated in figures 14 through 16. Fourth gear is not shown as no partial load data was obtained. The LSG 2000 exhibits typical behavior in that overall efficiency falls as load decreases. The

overall efficiency trend, with respect to output speed, remains the same throughout the load range, though it becomes progressively more pronounced as the load decreases.

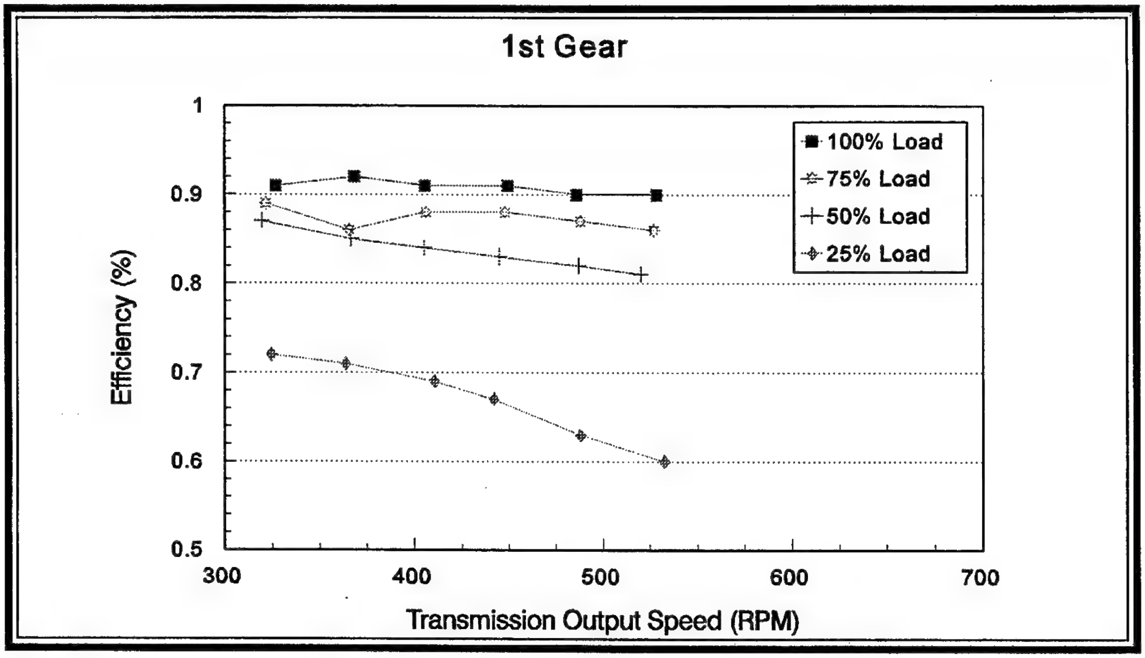

Figure 14 : LSG 2000 First Gear Part Load Efficiencies

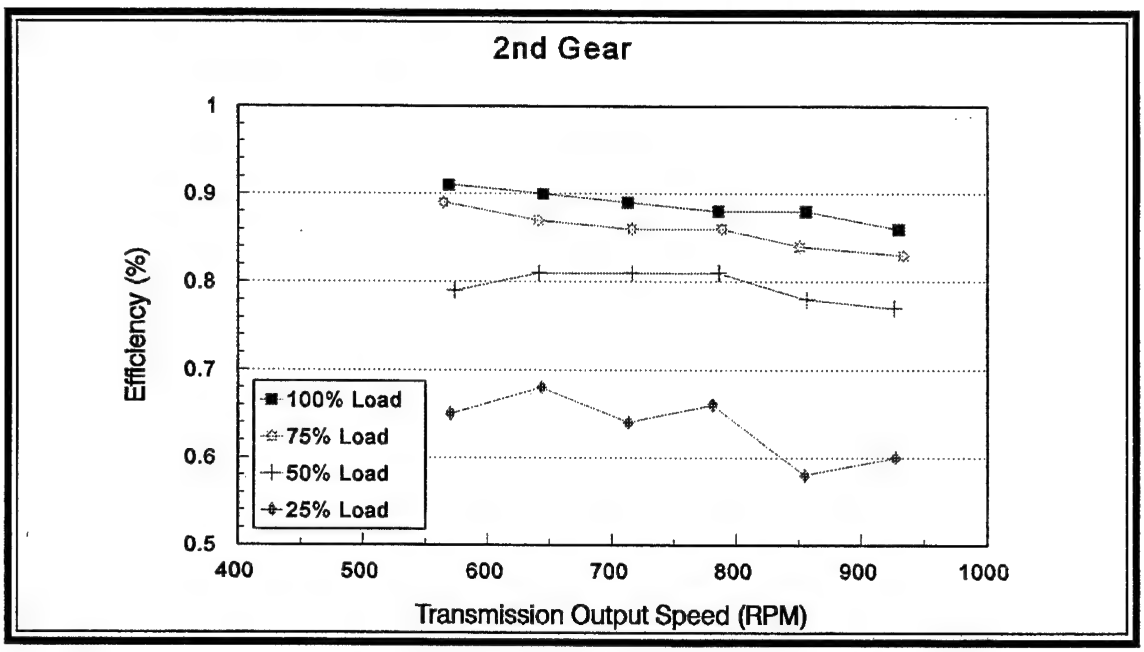

Figure 15: LSG 2000 Second Gear Part Load Efficiencies

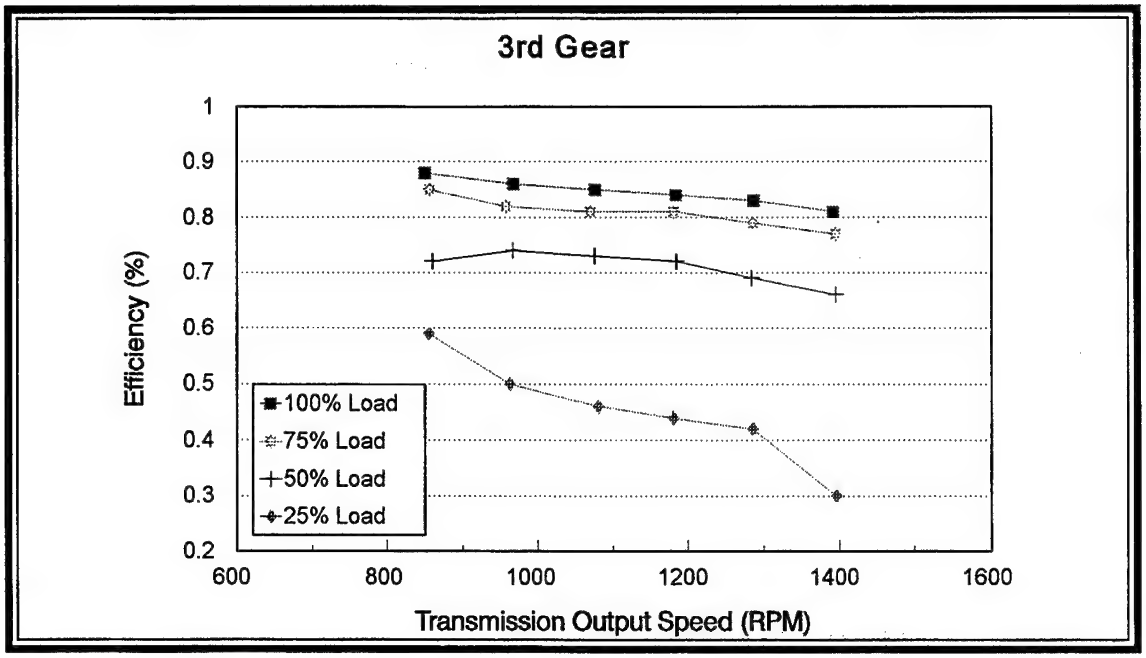

Figure 16: LSG 2000 Third Gear Part Load Efficiencies

In addition to testing the LSG 2000 in the lock-up condition, efficiencies in converter mode were also desired. Testing was performed to this end but analysis of the data generated during the third gear converter test indicated that an error in measurement or setup existed. Based on the chance that first gear or second gear converter data could also be erroneous, and since no further testing was possible, all converter data was assumed questionable and has been removed from the data that is presented in appendix B.

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APPENDIX A

TEST PROGRAM FOR ZF LSG 2000 TRANSMISSION
Revised 8/29/96

TITLE: ZF LSG 2000 Transmission Performance and Efficiency Testing.

OBJECTIVE: The objective is to verify the performance and efficiency characteristics for comparison with similar U.S. built transmissions.

OUTLINE OF TEST:

1. Installation and Instrumentation of Test Equipment.
2. Calibration of Instrumentation .
3. Transmission Set-up
4. Transmission Startup and No Load Checkout.
5. Transmission Testing

   a. Efficiency Testing using 10W oil
   b. Pivot Turn
   b. No Load Spin Loss Test
   c. Efficiency testing using 15W-40 oil

TEST EQUIPMENT:

1. ZF LSG 2000 Transmission rated at :

Max input power = 660 HP (492 kW)
Max input torque = 1425 lb-ft (1932 Nm)
Ratios

Input stage	0.917	
Forward gears:		
first gear	4.15	
second gear		2.36
third gear	1.57	
4th gear	1.00	
Reverse gears:		
first gear	4.52	
second gear	1.38	
Torque converter, stall:	2.80	

Summarizing gear: 1.296

2. Cummins VTA-903 Engine rated at:

   Max output power = 600 hp @2600 rpm
   Max output torque = 1241 ft-lb @ 2300 rpm

3. Two (2) General Electric Inductor Dynamometers Model 1G412
   One (1) 9800 ft-lb capacity torque meter
   Two (2) 25,000 capacity torque links
   Torque shafts
   Flex couplings
   Wiring Harness

4. Transmission oil complying with MIL-L-2104, SAE 10W
   Transmission oil complying with MIL-L-2104, SAE 15W-40

INSTRUMENTATION REQUIRED: The engine and transmission will be installed per the installation drawings. The engine and transmission will be instrumented to measure the following parameters.

DESCRIPTION	UNITS	RANGE
a. Performance - Engine		
Speed	revs/min	1600-2600
Torque	ft-lb	0-1241
Fuel flow	lbs/hr	0-280
b. Performance - Transmission		
Speed Out	revs/min	0-3000
Torque Out	ft-lb	0-9800
c. Pressures - Engine		
Oil Gallery	psi	0-100
Fuel Supply	psi	0-30
Intake Manifold	psi	0-30
Coolant Out	psi	0-30
Air Before Turbo	psi	0-1
d. Pressures - Transmission		
Oil Pressure from Oil Cooler	psi	
Oil Pressure to Oil Cooler	psi	60-160
Control Pressure Retarder On	psi	
Pressure after Retarder	psi	
Throttle Pressure	psi	

Control Pressure to gear	psi	
Pressure Before Converter	psi	60-160
Pressure After Converter	psi	60-160
Gear shift Pressure		

e. Temperatures - Engine

Coolant Temp	°F	230 max
Oil Gallery	°F	230 max
Oil Sump Temp	°F	270 max
Fuel Supply	°F	80-100
Exhaust After Turbo	°F	1500 max

f. Temperatures - Transmission

Oil Sump	°F	40-300
Trans Oil out of Cooler	°F	225-230 max
Trans Oil into Cooler	°F	250 max

g. Other Info Required

Test cell temperature	°F	40-100
Test cell Pressure	H_2O in	
Transmission coolant flow	gpm	0-65
Transmission oil flow	gpm	0-65
Water tower supply temp	°F	
Water tower supply pres	psi	
Water tower return temp	°F	
Pillow blocks	°F	

MAINTENANCE:

Transmission oil level should be checked at the end of every test day. Put reversing lever in neutral, have engine running at idle speed for approximately four (4) minutes. Oil level should lie between the two marks on the dipstick.

First oil change after approximately 50 hours operation. Subsequent oil changes after approximately 200 hours of operation.

Each time oil is changed the pressure filter element must be renewed and the suction screen cleaned. (See operators manual for instructions)

TRANSMISSION SETUP:

The transmission shall be installed in test cell #5 with the modified Cummins VTA-903 engine and associated test equipment and instrumentation.

Transmission cooler setup: connection for heat exchanger is M42x2, max flow rate is 80 gal/min. Top hole is in, bottom-out.

Fill transmission with approx 21 gallons of SAE 10W oil.

** Special Considerations**

Run through the range of 1300-1600 rpm without stopping for any length of time. This range has a mismatch problem with the turbocharger and could cause engine damage.

1. Set reversing gear in neutral. Start engine, shift reversing gear to forward, shift speed range lever to 4, run at idle for five (5) minutes. Visually check engine and transmission for external leaks. Shut down engine, check engine and transmission, hoses, fittings and connections for any leaks. Repair as necessary.
2. Restart engine and run at idle RPM. Operate engine and record data for 20 minutes, in five (5) minute intervals, to verify the validity of test cell equipment.
3. Put transmission in Speed Range 4 and slowly accelerate to 2600 RPM. Slowly decelerate engine to 1600 rpm, observe output shaft for rotational RPM. Increase rpm and listen for any unusual noise (ie metal grinding on metal and other very obviously strange sounds) from transmission. Decrease engine to idle RPM.
4. Change reversing gear to Reverse and speed range level to 2 and repeat last step.
5. Check transmission, engine, cooler and filter for leaks.

TRANSMISSION EFFICIENCY TESTING USING 10W OIL:

1. Test oil: SAE 10W
2. Test points (engine speed): 2600, 2400, 2200, 2000, 1800, 1600

NOTE: Allow system to stabilize for 5 minutes at each test point

3. Record data while in both convertor and lockup operating conditions.
4. Run engine at the following part loads, or, % of full power for given speeds: 100%, 75%, 50%, 25% in gears: 1, 2, 3, 4, R1, R2
5. Record: engine speed, engine torque, turbine speed, transmission output speeds and torques, fuel flow rate, transmission oil temperature before and after cooler and transmission oil flow rate.

PIVOT TURN TEST:

1. Test oil: SAE 10W
2. Place engine in idle and transmission in neutral, in convertor mode.
3. Allow dynamometers to come to a complete stop.
4. Activate the pivot steer condition by turning on the "PVT" switch.
5. Set transmission into gear 1.
6. Record below data for tests points: 1600, 1800, 2000, 2200, 2400, 2600RPM.

NOTE: Allow system to stabilize for 5 minutes at each test point

7. Record data in both convertor and lockup operating modes.
8. Perform the above procedure for gears 1, 2, 3, 4, R1 and R2 while at 100% load and 50% load.

Data to be recorded: Engine speed, engine torque, fuel flow rate, turbine speed, transmission output speeds and torques, transmission oil flow rate, transmission oil temperature before and after cooler

NO LOAD SPIN LOSS TEST:

The spin loss test will determine how much horsepower it will take to spin the trans in each gear, converter and lock-up, and how many input losses there are, neutral mode.

1. Test oil: SAE 10W and SAE 15W-40
2. Disconnect transmission output shafts from dynamometers.
3. Heat trans oil to 200°F.
4. Set steer to straight ahead.
5. Put transmission in neutral and log following data after stabilizing each point for 5 minutes. Log the following points in neutral: 1000, 1200, 1800, 2200, 2600 RPM.
6. Run transmission in lock up and in converter mode: Upon stabilization of each point (roughly 5 minutes), record data for: engine speed, engine torque, turbine speed, transmission oil temp to cooler, trans oil temp from cooler, transmission output speed.
   Run each gear range 1, 2, 3, 4, R1, R2
   Engine speed 1000,1600, 1800, 2000, 2200, 2400, 2600
7. Drain SAE 10W oil and replace with SAE 15W-40 Oil and repeat above steps.

TRANSMISSION EFFICIENCY TESTING USING 15W-40 OIL:

1. Test oil: SAE 15W-40
2. Test points (engine speed): 2600, 2400, 2200, 2000, 1800, 1600

NOTE: Allow system to stabilize for 5 minutes at each test point

3. Record data while in both convertor and lockup operating conditions.

4. Run engine at the following part loads, or, % of full power for given speeds: 100%, 75%, 50%, 25% in gears: 1, 2, 3, 4, R1, R2

5. Record: engine speed, engine torque, turbine speed, transmission output speeds and torques, fuel flow rate, transmission oil temperature before and after cooler and transmission oil flow rate.

APPENDIX B

Test Data

TACOM Run# 349 started 08/27/96 at 09:54 Page 2
Test name: 2 ND GEAR FULL POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Data Table

Wall Time	09:54	09:56	09:57	10:00	10:02	10:05
ISPEED rpm	2606	2606	2400	2368	2204	2238
ITORQUE lb-ft	1210	1204	1251	1256	1270	1268
IBHP HP	600	597	571	566	532	540
TURBINE RPM	2842	2843	2619	2584	2405	2441
CONVERTOR RATIO	1	1	1	1	1	1
NSPEED rpm	931	931	857	845	787	799
NTORQUE lb-ft	1402	1408	1485	1490	1514	1521
SSPEED RPM	929	928	855	843	785	797
STORQUE lb-ft	1527	1531	1609	1614	1641	1635
TRANS OIL GPM	59.83	59.75	58.43	57.93	56.39	56.64
TRANS OIL MAIN psi	264.7	264.1	261.5	260.1	258.3	259.2
RETARDER CONTROL psi	2.8	3.1	3.3	3.8	3.9	3.8
AFTER RETARDER psi	0.4	0.4	0.4	0.3	0.3	0.3
WATER TOWER psi	66.5	65.8	56.3	65.8	55.4	63.7
OIL AFTER COOLER psi	70.1	69.5	67.8	67.2	66.4	67.0
OIL BEFORE COOLER psi	131.5	130.3	123.2	120.7	115.4	117.1
OIL BEFORE CONVERTOR psi	87.1	86.6	83.8	82.8	82.1	82.3
OIL AFTER CONVERTOR psi	108.6	107.7	104.2	102.8	99.8	100.8
TRANS SHIFT psi	58.4	58.0	57.6	58.1	58.4	58.3
CELL AMBIENT 'F	69.5	69.8	69.4	69.9	69.8	69.9
OIL TRANS SUMP 'F	220.9	229.4	234.1	240.8Y	237.3	232.1
OIL BEFORE COOLER 'F	220.6	229.0	233.8	242.1Y	241.2Y	237.0
OIL AFTER COOL;ER 'F	218.8	227.4	232.3	237.3	231.5	225.0
WATER BEFORE COOLER 'F	163.1	182.0	191.8	90.3	81.4	79.6
WATER AFTER COOLER 'F	166.9	177.2	184.1	228.0	213.0	205.0

TACOM Run# 349 started 08/27/96 at 09:54 Page 2.1
Test name: 2 ND GEAR FULL POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Wall Time	10:09	10:11	10:16	10:18	10:20	10:22
ISPEED rpm	2003	1999	1817	1808	1598	1598
ITORQUE lb-ft	1273	1270	1274	1275	1233	1233
IBHP HP	485	483	440	438	375	375
TURBINE RPM	2187	2182	1982	1972	1745	1745
CONVERTOR RATIO	1	1	1	1	1	1
NSPEED rpm	714	714	649	646	568	570
NTORQUE lb-ft	1555	1531	1551	1553	1548	1525
SSPEED RPM	713	712	648	644	567	568
STORQUE lb-ft	1672	1656	1669	1667	1661	1641
TRANS OIL GPM	52.50	51.90	45.64	45.41	39.06	38.88
TRANS OIL MAIN psi	256.5	256.4	253.7	253.7	250.7	251.1
RETARDER CONTROL psi	3.5	3.5	3.6	3.6	3.5	3.4
AFTER RETARDER psi	0.3	0.4	0.4	0.4	0.3	0.3
WATER TOWER psi	66.2	64.3	59.3	55.2	59.8	66.2
OIL AFTER COOLER psi	62.5	63.1	57.7	57.4	51.8	52.4
OIL BEFORE COOLER psi	106.8	107.2	97.5	97.2	90.6	92.2
OIL BEFORE CONVERTOR psi	75.9	76.3	68.1	68.0	59.5	60.2
OIL AFTER CONVERTOR psi	92.9	93.9	84.4	84.2	80.2	82.4
TRANS SHIFT psi	58.2	57.7	57.0	57.4	56.9	57.2
CELL AMBIENT 'F	70.0	70.1	70.1	70.7	70.7	70.8
OIL TRANS SUMP 'F	227.2	231.7	233.5	231.3	229.2	226.1
OIL BEFORE COOLER 'F	232.4	234.0	236.4	235.0	233.0	230.0
OIL AFTER COOL;ER 'F	221.1	227.8	228.4	225.0	221.6	218.6
WATER BEFORE COOLER 'F	79.8	81.8	82.1	80.0	80.6	80.0
WATER AFTER COOLER 'F	198.8	223.5	225.6	213.7	209.3	207.0

TACOM Run# 354 started 08/28/96 at 09:12 Page 2
Test name: 2 ND GEAR 75 % POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Data Table

Wall Time	09:12	09:13	09:17	09:18	09:24	09:28
ISPEED rpm	2608	2618	2414	2390	2209	2214
ITORQUE lb-ft	913	908	929	927	947	955
IBHP HP	453	452	427	421	398	402
TURBINE RPM	2842	2857	2633	2607	2409	2416
CONVERTOR RATIO	1	1	1	1	1	1
NSPEED rpm	930	934	860	851	788	789
NTORQUE lb-ft	991	998	1042	1041	1064	1098
SSPEED RPM	929	933	859	851	788	788
STORQUE lb-ft	1114	1123	1167	1163	1184	1217
TRANS OIL GPM	59.11	59.05	58.05	57.94	56.65	56.72
TRANS OIL MAIN psi	263.2	263.3	261.3	261.1	259.1	258.8
RETARDER CONTROL psi	3.7	3.7	3.7	3.6	3.6	3.9
AFTER RETARDER psi	0.4	0.4	0.4	0.4	0.4	0.4
WATER TOWER psi	56.2	58.6	56.1	64.9	65.0	59.7
OIL AFTER COOLER psi	69.2	69.2	67.9	67.8	66.5	66.3
OIL BEFORE COOLER psi	128.8	129.2	123.2	122.7	116.4	116.2
OIL BEFORE CONVERTOR psi	86.5	86.4	84.4	84.5	82.4	82.0
OIL AFTER CONVERTOR psi	107.0	107.3	104.3	104.0	100.5	100.2
TRANS SHIFT psi	58.6	58.7	58.6	58.6	57.7	57.5
CELL AMBIENT 'F	56.0	66.0	66.0	66.0	65.8	65.9
OIL TRANS SUMP 'F	232.7	231.5	228.6	228.0	230.5	233.4
OIL BEFORE COOLER 'F	235.1	235.1	232.8	232.2	232.8	235.8
OIL AFTER COOL;ER 'F	228.3	226.0	223.2	222.7	227.0	229.7
WATER BEFORE COOLER 'F	77.5	75.9	76.3	76.3	77.9	78.0
WATER AFTER COOLER 'F	226.2	217.3	211.7	210.8	224.3	227.4

TACOM Run# 354 started 08/28/96 at 09:12 Page 2.1
Test name: 2 ND GEAR 75 % POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Wall Time	09:40	09:40	09:41	09:42	09:44	09:46
ISPEED rpm	1997	2009	1795	1799	1611	1591
ITORQUE lb-ft	964	953	961	961	948	950
IBHP HP	366	364	328	329	290	287
TURBINE RPM	2180	2192	1958	1963	1754	1736
CONVERTOR RATIO	1	1	1	1	1	1
NSPEED rpm	711	716	640	641	577	565
NTORQUE lb-ft	1131	1095	1114	1124	1073	1147
SSPEED RPM	710	716	640	641	576	564
STORQUE lb-ft	1248	1216	1233	1236	1186	1256
TRANS OIL GPM	52.32	52.44	45.12	45.41	37.82	38.52
TRANS OIL MAIN psi	256.6	256.8	254.0	253.9	251.2	250.6
RETARDER CONTROL psi	3.6	3.5	3.5	3.5	3.6	3.6
AFTER RETARDER psi	0.4	0.4	0.4	0.4	0.4	0.4
WATER TOWER psi	66.3	58.5	66.4	63.3	66.4	66.3
OIL AFTER COOLER psi	62.3	63.0	57.4	57.3	52.7	51.6
OIL BEFORE COOLER psi	106.6	107.7	97.7	97.7	91.9	90.6
OIL BEFORE CONVERTOR psi	76.2	77.3	68.5	68.4	61.4	59.8
OIL AFTER CONVERTOR psi	92.9	93.8	84.9	85.0	81.5	80.5
TRANS SHIFT psi	57.8	57.8	56.9	56.8	56.1	56.0
CELL AMBIENT 'F	65.6	65.8	65.5	65.6	65.8	65.8
OIL TRANS SUMP 'F	227.0	227.9	228.8	229.3	230.1	230.6
OIL BEFORE COOLER 'F	229.4	230.0	230.5	231.1	231.8	232.1
OIL AFTER COOL;ER 'F	223.0	223.9	224.5	225.4	225.2	225.9
WATER BEFORE COOLER 'F	77.6	78.0	78.2	78.7	78.9	78.8
WATER AFTER COOLER 'F	219.7	221.1	222.4	223.7	224.2	224.6

TACOM Run# 355 started 08/28/96 at 10:00 Page 2
Test name: 2 ND GEAR 50 % POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Data Table

Wall Time	10:00	10:01	10:03	10:06	10:13	10:15
ISPEED rpm	2596	2600	2406	2405	2209	2208
ITORQUE lb-ft	611	611	626	634	642	634
IBHP HP	302	302	286	290	270	266
TURBINE RPM	2832	2837	2626	2623	2411	2409
CONVERTOR RATIO	1	1	1	1	1	1
NSPEED rpm	925	927	857	857	787	786
NTORQUE lb-ft	608	610	647	650	668	668
SSPEED RPM	924	926	857	856	787	786
STORQUE lb-ft	717	718	758	760	777	778
TRANS OIL GPM	58.97	58.94	58.00	57.98	56.70	56.65
TRANS OIL MAIN psi	262.9	262.9	261.2	261.4	259.0	258.7
RETARDER CONTROL psi	3.7	3.7	3.7	3.6	3.6	3.7
AFTER RETARDER psi	0.4	0.4	0.3	0.4	0.4	0.4
WATER TOWER psi	66.3	60.8	62.6	66.4	66.4	62.6
OIL AFTER COOLER psi	68.9	68.9	67.7	67.8	66.2	66.3
OIL BEFORE COOLER psi	128.0	128.0	122.4	122.8	116.2	115.8
OIL BEFORE CONVERTOR psi	86.3	86.3	84.6	84.6	82.4	82.2
OIL AFTER CONVERTOR psi	106.5	106.6	103.9	104.1	100.4	100.0
TRANS SHIFT psi	58.4	58.4	58.4	58.7	57.8	57.5
CELL AMBIENT 'F	65.5	65.4	65.6	65.5	66.0	66.0
OIL TRANS SUMP 'F	231.6	231.3	228.8	226.9	230.3	232.1
OIL BEFORE COOLER 'F	234.8	234.8	232.9	231.0	232.2	233.9
OIL AFTER COOL;ER 'F	226.8	226.1	223.5	221.6	226.9	228.6
WATER BEFORE COOLER 'F	76.8	76.3	76.0	76.5	78.3	78.9
WATER AFTER COOLER 'F	222.6	219.4	213.8	211.0	224.2	225.1

TACOM Run# 355 started 08/28/96 at 10:00 Page 2.1
Test name: 2 ND GEAR 50 % POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Wall Time	10:17	10:19	10:21	10:22	10:24
ISPEED rpm	1999	2011	1799	1799	1606
ITORQUE lb-ft	637	633	644	646	613
IBHP HP	242	242	220	221	187
TURBINE RPM	2181	2194	1963	1962	1749
CONVERTOR RATIO	1	1	1	1	1
NSPEED rpm	713	716	641	642	574
NTORQUE lb-ft	670	669	699	685	632
SSPEED RPM	712	716	640	641	573
STORQUE lb-ft	778	778	808	792	736
TRANS OIL GPM	51.28	51.85	45.17	44.86	38.08
TRANS OIL MAIN psi	256.2	256.3	253.7	254.0	251.3
RETARDER CONTROL psi	3.7	3.7	3.6	3.6	3.5
AFTER RETARDER psi	0.4	0.4	0.4	0.4	0.4
WATER TOWER psi	65.9	64.1	66.5	66.4	64.9
OIL AFTER COOLER psi	62.3	62.7	56.9	57.3	52.7
OIL BEFORE COOLER psi	106.2	107.0	97.7	97.9	91.8
OIL BEFORE CONVERTOR psi	76.0	76.6	68.2	68.5	61.5
OIL AFTER CONVERTOR psi	92.5	93.4	85.4	85.5	81.5
TRANS SHIFT psi	57.0	57.3	56.9	57.1	56.6
CELL AMBIENT 'F	65.7	66.0	66.3	66.5	66.2
OIL TRANS SUMP 'F	232.3	231.0	228.4	227.2	225.6
OIL BEFORE COOLER 'F	234.5	233.9	231.8	230.8	229.0
OIL AFTER COOL;ER 'F	228.1	226.1	222.8	221.6	219.1
WATER BEFORE COOLER 'F	77.7	77.0	76.3	76.3	76.8
WATER AFTER COOLER 'F	226.8	223.1	218.5	217.1	215.4

TACOM Run# 356 started 08/28/96 at 10:39 Page 2
Test name: 2 ND GEAR 25 % POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Data Table

Wall Time	10:39	10:40	10:41	10:43	10:44	10:45
ISPEED rpm	2604	2394	2400	2200	2195	2009
ITORQUE lb-ft	308	315	312	323	320	322
IBHP HP	152	143	142	135	133	123
TURBINE RPM	2842	2616	2618	2400	2397	2192
CONVERTOR RATIO	1	1	1	1	1	1
NSPEED rpm	927	852	854	784	781	715
NTORQUE lb-ft	219	252	218	245	258	254
SSPEED RPM	927	852	855	784	781	716
STORQUE lb-ft	303	335	296	323	340	333
TRANS OIL GPM	58.94	57.91	57.81	56.46	56.57	52.28
TRANS OIL MAIN psi	262.9	260.9	261.1	259.0	258.9	256.8
RETARDER CONTROL psi	3.7	3.7	3.6	3.6	3.6	3.6
AFTER RETARDER psi	0.4	0.4	0.4	0.4	0.4	0.4
WATER TOWER psi	63.7	66.3	66.3	66.0	65.1	66.3
OIL AFTER COOLER psi	68.9	67.7	67.9	65.4	66.3	62.9
OIL BEFORE COOLER psi	128.0	122.1	122.5	116.2	116.1	107.1
OIL BEFORE CONVERTOR psi	86.0	84.0	84.8	82.5	82.5	77.0
OIL AFTER CONVERTOR psi	106.6	103.8	104.1	100.4	100.5	92.9
TRANS SHIFT psi	58.7	58.6	58.7	58.3	58.3	57.7
CELL AMBIENT 'F	67.6	67.6	67.6	67.9	68.0	68.2
OIL TRANS SUMP 'F	229.6	228.0	227.0	225.3	225.6	227.3
OIL BEFORE COOLER 'F	233.2	232.1	231.1	229.3	228.6	229.1
OIL AFTER COOL;ER 'F	224.2	223.1	222.1	220.4	221.5	223.4
WATER BEFORE COOLER 'F	76.3	76.3	75.9	76.2	75.8	78.2
WATER AFTER COOLER 'F	214.8	212.9	211.9	210.6	214.5	219.8

TACOM Run# 356 started 08/28/96 at 10:39 Page 2.1
Test name: 2 ND GEAR 25 % POWER Component: LSG 2000 TRANSMISSION : Operator: ROGER

Wall Time	10:46	10:51	10:53
ISPEED rpm	2002	1808	1605
ITORQUE lb-ft	322	323	307
IBHP HP	122	111	93
TURBINE RPM	2185	1973	1751
CONVERTOR RATIO	1	1	1
NSPEED rpm	713	643	570
NTORQUE lb-ft	254	270	270
SSPEED RPM	713	644	570
STORQUE lb-ft	334	351	349
TRANS OIL GPM	51.74	45.47	38.74
TRANS OIL MAIN psi	256.6	253.7	250.6
RETARDER CONTROL psi	3.5	3.6	3.6
AFTER RETARDER psi	0.4	0.4	0.3
WATER TOWER psi	65.9	65.5	55.7
OIL AFTER COOLER psi	62.3	57.1	51.9
OIL BEFORE COOLER psi	106.4	97.9	90.8
OIL BEFORE CONVERTOR psi	76.3	68.1	60.1
OIL AFTER CONVERTOR psi	92.1	85.3	80.4
TRANS SHIFT psi	57.6	56.8	55.9
CELL AMBIENT 'F	68.2	67.8	67.8
OIL TRANS SUMP 'F	227.9	230.4	230.6
OIL BEFORE COOLER 'F	229.7	231.9	232.1
OIL AFTER COOL;ER 'F	224.8	227.1	226.5
WATER BEFORE COOLER 'F	78.9	80.1	79.8
WATER AFTER COOLER 'F	221.4	225.0	225.1

APPENDIX C

Sample Calculations

Calculations are based on full load performance in transmission gear 2 with a wall time of 9:56.

Transmission Power Output:

$$Power\ Out\ of\ Transmission = \frac{(Ntorque + Storque) \times (\frac{Nspeed + Sspeed}{2})}{5252.11}$$

$$Power\ Out\ of\ Transmission = \frac{(1408\,ft\text{-}lb + 1531\,ft\text{-}lb) \times (\frac{931\,RPM + 928\,RPM}{2})}{5252.11}$$

$$Power\ Out\ of\ Transmission = 520.13\,HP$$

System Efficiency:

$$Efficiency = \frac{Power\ Out\ of\ Transmission}{Power\ Out\ of\ Engine} \times 100\%$$

$$Efficiency = \frac{520\ HP}{597\ HP} \times 100\%$$

$$Efficiency = 87.1\%$$

Transmission Output Speed (%):

$$\textit{Maximum Output Speed} = \textit{maximum engine speed} \div \textit{input gear ratio}$$
$$\div \textit{converter ratio} \div \textit{trans gear 4 ratio}$$
$$\div \textit{summarizing gear ratio}$$

$$\textit{Maximum Output Speed} = 2600\,RPM \div .917 \div 1.00 \div 1.00 \div 1.296$$

$$\textit{Maximum Output Speed} = 2187.75\,RPM$$

$$\textit{Trans Output Speed (\%)} = \frac{\frac{\textit{Sspeed} + \textit{Nspeed}}{2}}{\textit{Maximum Output Speed}} \times 100\%$$

$$\textit{Trans Output Speed (\%)} = \frac{\frac{931\,RPM + 928\,RPM}{2}}{2187.75\,RPM} \times 100\%$$

$$\textit{Trans Output Speed (\%)} = 42.49\%$$

APPENDIX D

Failure Analysis

As explained in the document, a failure in the system occurred while attempting to attain data for the transmission operating in fourth gear at 2200 rpm. This failure occurred in the north output side of the transmission. The pillow block involved in the failure can be seen in the forefront toward the right side of figure D-1. This pillow block moved slightly toward the transmission which is the cause of this. From what can be determined, the most probable cause is that a resonant frequency was achieved which, in turn, loosened up the bolts holding the pillow block stand enough to allow this slight, yet catastrophic movement.

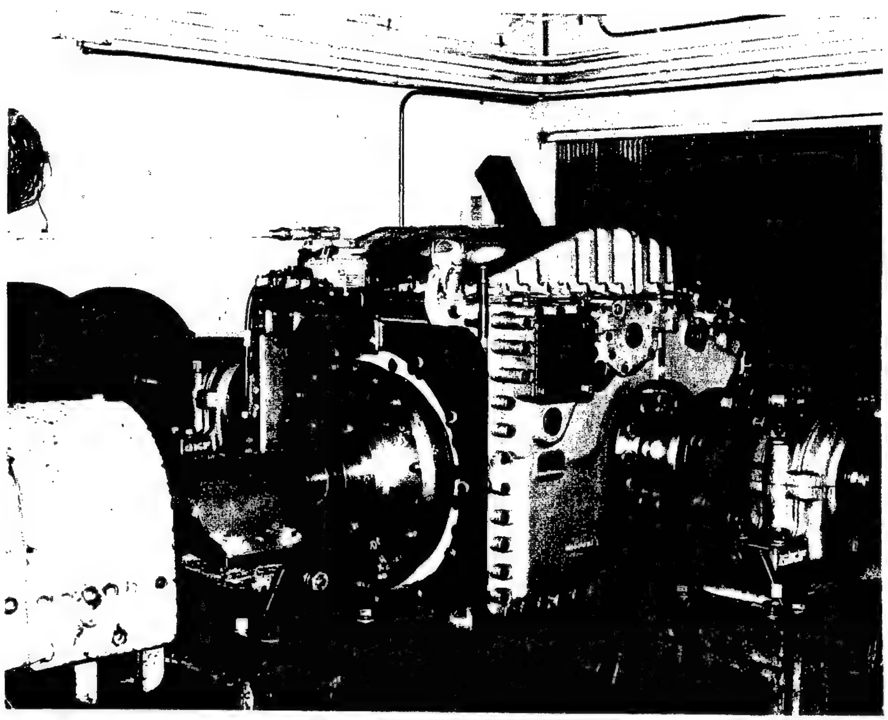


Figure D-1: Transmission Setup Showing Side That Would Fail

As the pillow block and stand moved, the rings between the pillow block and the splined shaft tilted. The rings then began rubbing into and scoring the splined shaft generating the heat that started the fire. From figure D-2 it can be observed where the scoring was taking place. The fire itself occurred in the adapter plate area. This is about one foot or so away from the transmission. The two transmission oil lines were scorched by the flames. A good indication of the location of the fire along the output shaft can be seen in figure D-3 by noticing the tan scorch marks on the oil lines.

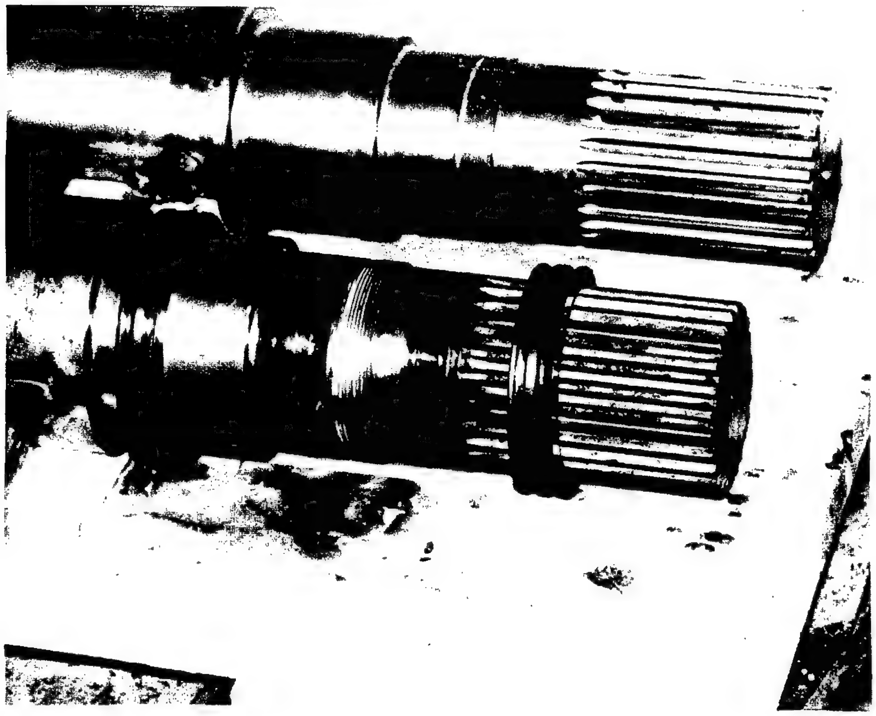


Figure D-2: TACOM's Splined Output Shaft

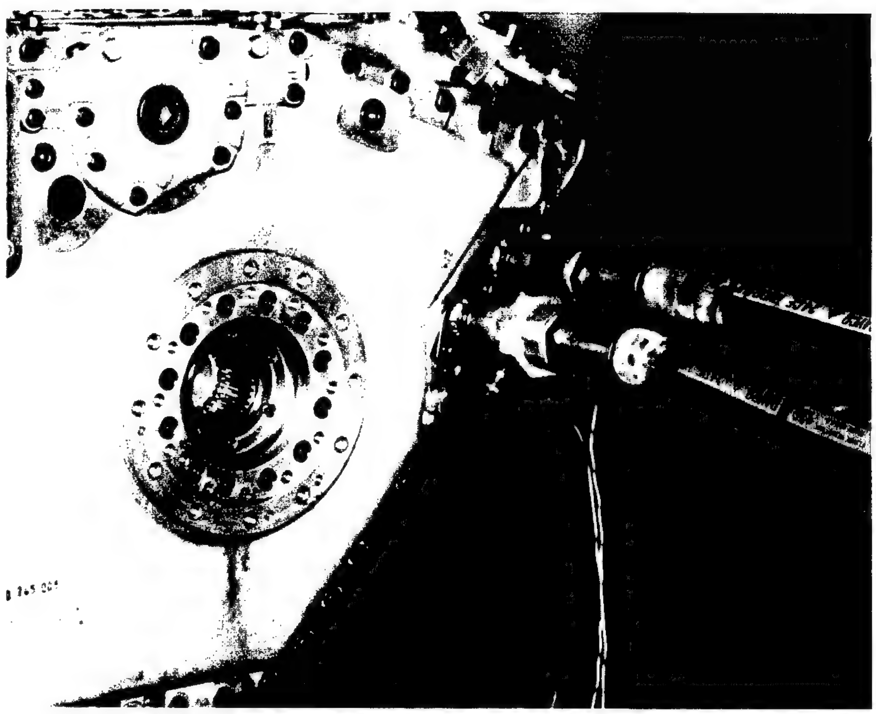


Figure D-3: Transmission After Removing Output Subassembly

During the movement of the pillow block, the adapter plates were moved enough such that the dust deflector, figure D-4, was pressed in between the screws used to hold the transmission's output shaft to its housing. The dust deflector was forced into contact with the mounting plate. The result of the dust deflector's movement generated both heat and extensive physical damage. The combination of the heat generated by the dust deflector/screw contact and that of the mounting bracket/dust deflector, figures D-4 and D-5 respectively, was such to cause damage to further components of this subassembly.

The main component of the damaged subassembly is the transmission's splined output shaft. This item is shown in figure D-7. It appears relatively undamaged, though it has been colored by the heat generated during the failure. The two main internal components damaged were the oil seal and the bearing. Before taking off the output transmission assembly it was evident that the oil seal had failed as a small amount of oil had leaked down the side of the transmission (reference figure D-3). Upon disassembly, the seal was found to have split and is shown, exaggerated, in figure D-8. The bearing, figure D-9 does not appear physically damaged aside from some discoloration. However, upon disassembly and inspection, it was noted that the bearing didn't spin freely and sounded like there were parts coming into contact that should not have been.

Figure D-4: Dust Deflector Showing Screw Contact Wear

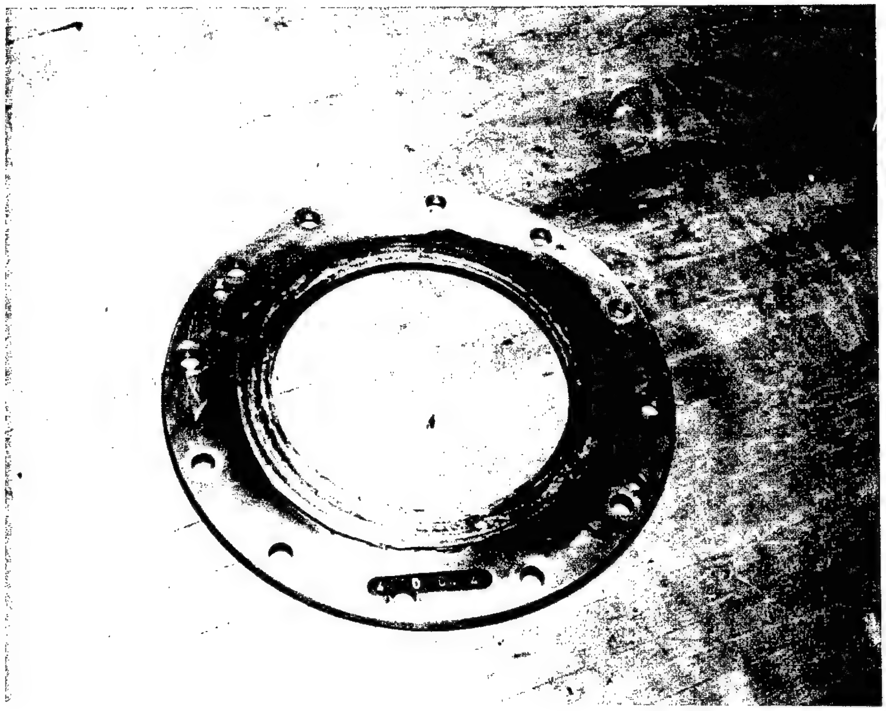


Figure D-5: Mounting Plate Side Facing Dust Deflector

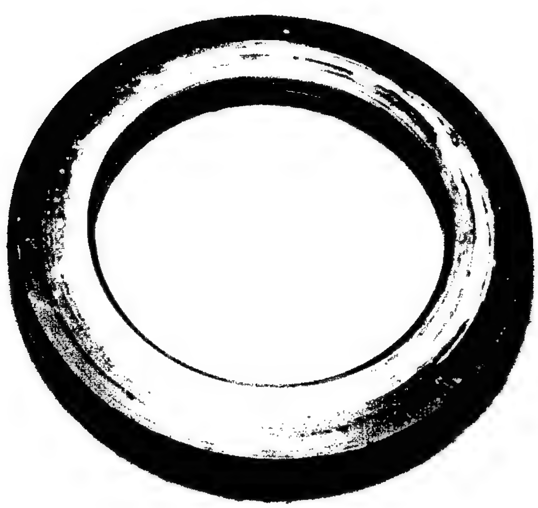


Figure D-6: Dust Deflector Side in Contact with Mounting Plate

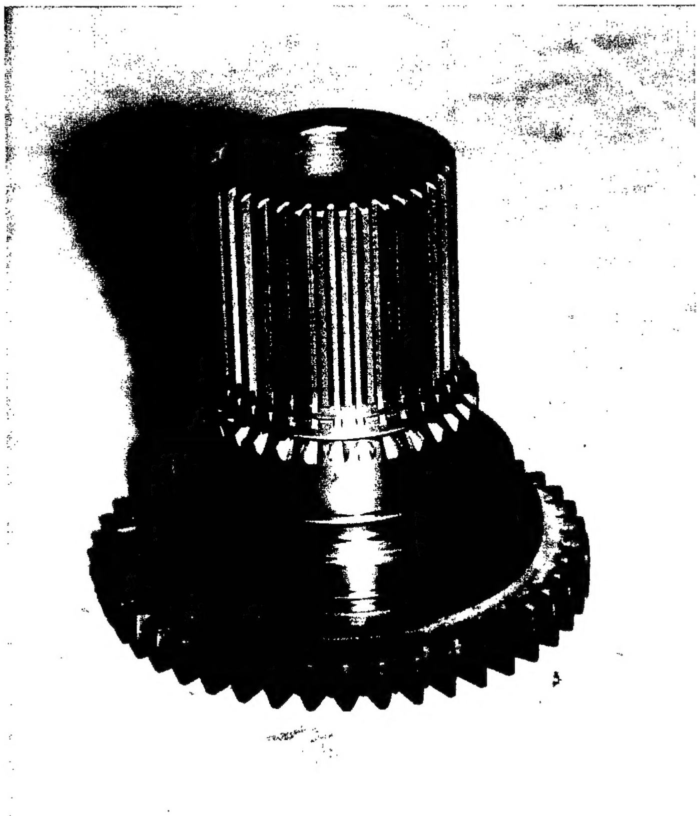


Figure D-7: Transmission Output Assembly Splined Shaft

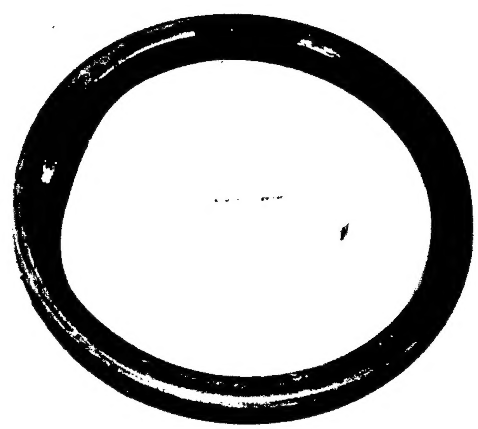
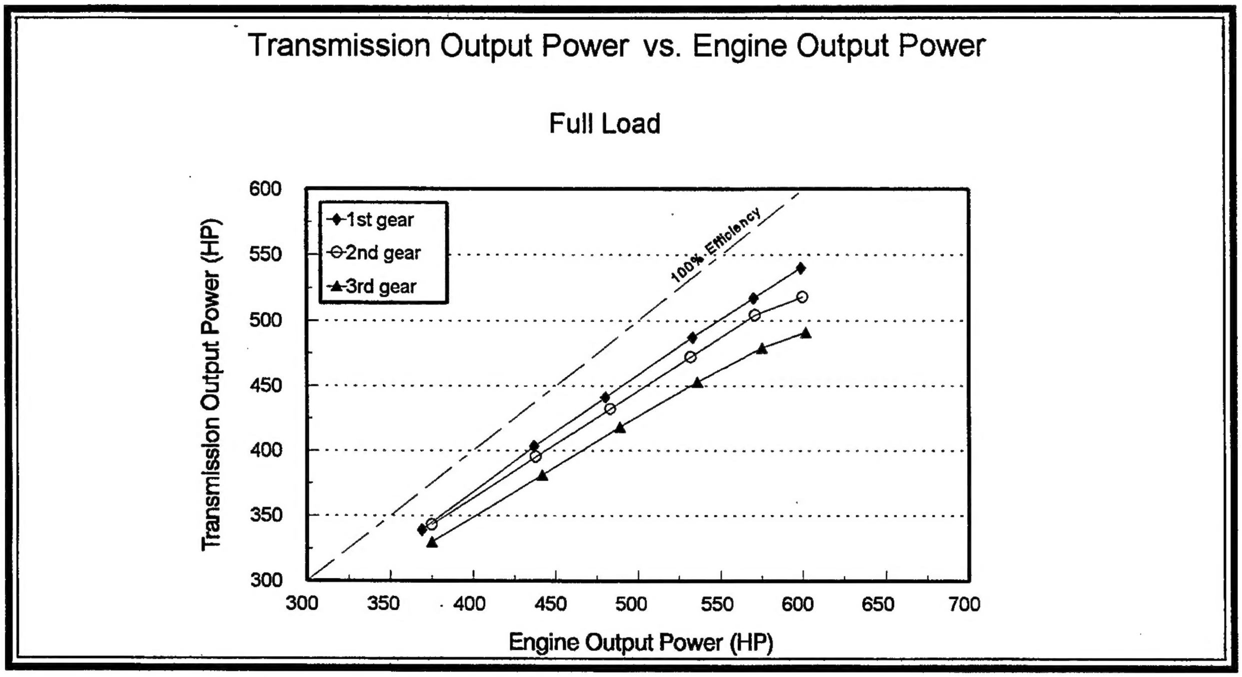


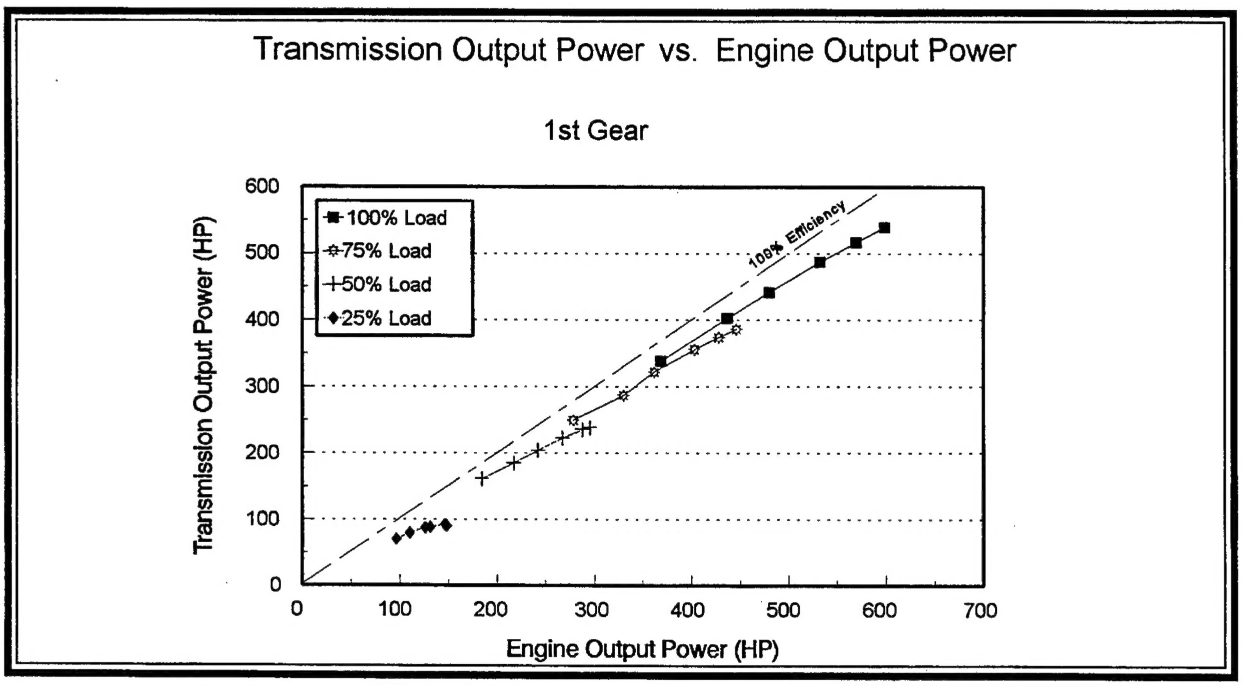
Figure D-8: Transmission Output Assembly Oil Seal

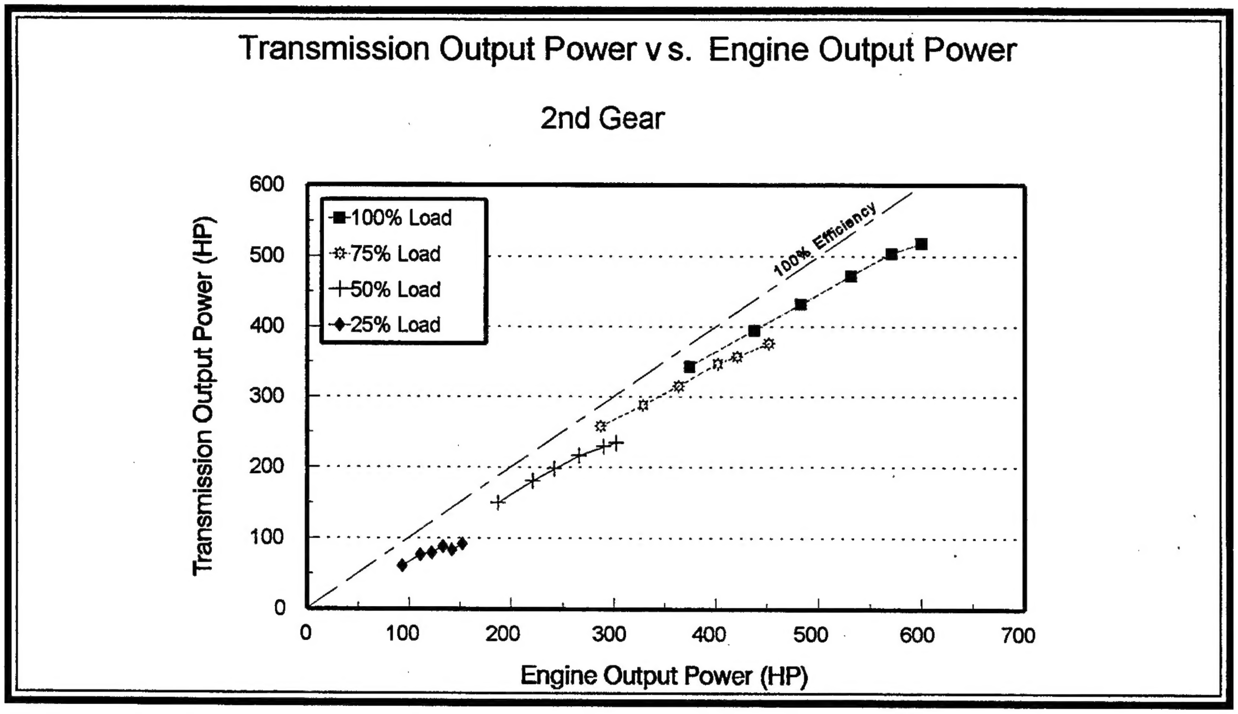
Figure D-9: Transmission Output Assembly Ball Bearing

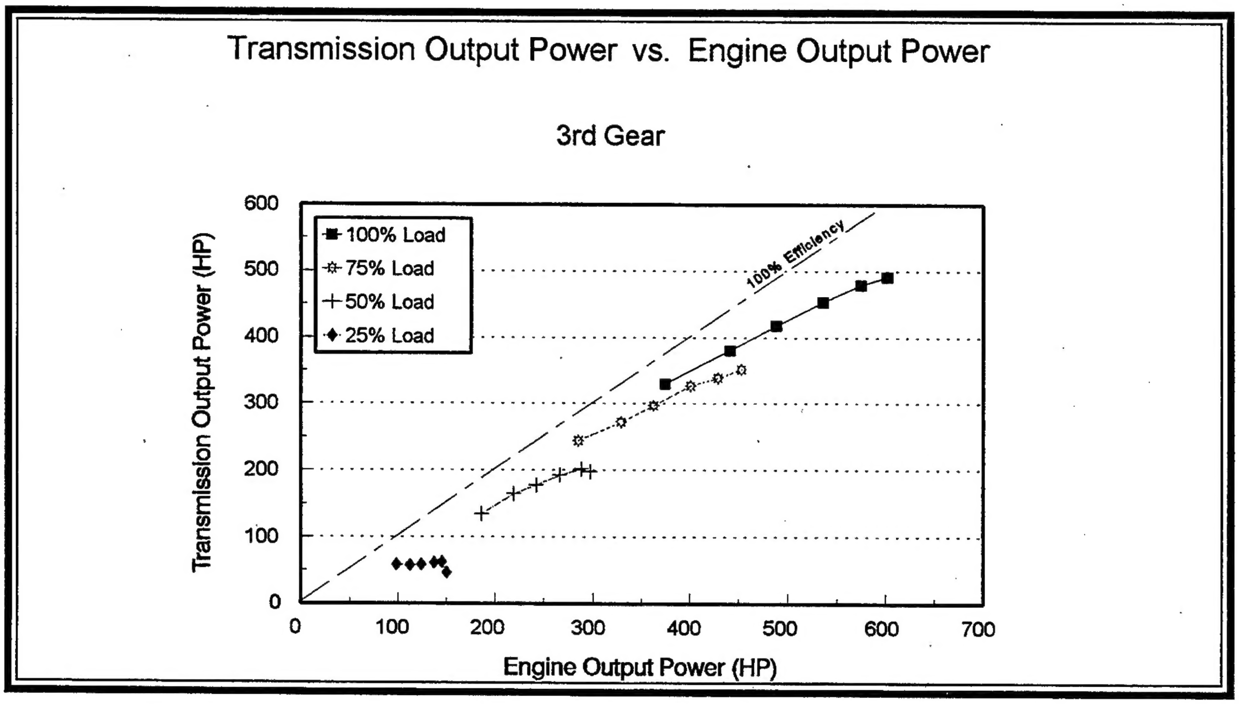
APPENDIX E

Additional Transmission Performance Curves






Transmission Output Power vs. Engine Output Power
2nd Gear
Transmission Output Power (HP)
Engine Output Power (HP)
100% Load
75% Load
50% Load
25% Load
100% Efficiency
0
100
200
300
400
500
600
700


Transmission Output Power vs. Engine Output Power
3rd Gear
Transmission Output Power (HP)
Engine Output Power (HP)
100% Load
75% Load
50% Load
25% Load
100% Efficiency
0
100
200
300
400
500
600
700